Macrobenthic and Chemical Analysis of Papermill Creek

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Executive Summary

Macrobenthic and chemical analyses were conducted during the period August 1998 to April 1999 to assess water quality in Papermill Creek, located along the Colonial Parkway near Williamsburg, VA. Both the abundance and diversity of macrobenthos were extremely low, indicating severe disturbance. Chemical results suggested one of the likely reasons for this: the stream was unusually high in dissolved materials, with a level above that normally considered "fresh." Additionally, the water was unusually warm, with a temperature at times about 10 °C higher than expected. Both these conditions apparently are due to the fact that a significant portion of the stream's flow derives from the discharge of deep ground water used for cooling purposes by Colonial Williamsburg. Additionally, the stream probably suffers from the general adverse effects of urban run-off, and from the large, rapid changes in water chemistry that occur when the stream's high-solute water is diluted for short periods by storm events and then returns to higher levels again. A recent oil spill also may have had a significant, but unknown, effect on organismal diversity. Beyond maintaining the land in the immediate vicinity of the stream in as natural a state as possible, there is probably little that CNHP can do to support appropriate natural conditions in Papermill Creek, given that the areas and processes impacting the stream are not within its control.

Introduction

The following report describes the macrobenthic assemblage and selected chemical characteristics of Papermill Creek, located along the Colonial Parkway in Williamsburg, Va. Prior to this study no data were available for the stream, although it was assumed to be impacted by general urban run-off. For the biomonitoring work the original intention was to conduct an assessment that would include development of a variety of standard metrics, based on family-level identification, to provide a relatively-detailed quantitative interpretation. However, diversity of benthos is extremely low, probably due to a variety of serious problems including a spill of fuel oil in April 1998. Therefore a relatively simple description and interpretation of findings is sufficient to characterize the stream.

Stream and Drainage Area

The study area is located in Williamsburg and James City County, extending southward approximately 1600 m from Newport Ave. For reference, see Map 1 depicting the area in 1952, and Map 2 from 1984. The exact historical application of the name "Papermill Creek" to the various small drainages in this area is not known. However, "Papermill Creek" proper should probably be used only in reference to the single third-order stream extending from College Creek upstream to the point where the flow from the golf course enters. This portion includes the site where the paper mill giving the stream its name was located. Above this area the stream is formed by a confluence of two second order streams that in turn derive from a variety of first and second order flows. Most of these first and second order streams have been modified by human activity, including, variously, damming to construct ponds, complete destruction by urbanization, and (as described below) the introduction of deep groundwater to the surface. A beaver pond is located in the area between the two Parkway overlooks.

The work described here was conducted along portions of the stream in close proximity to the Colonial Parkway, specifically: 1) the flow beginning immediately south of Newport Avenue and extending along the parkway to the confluence with the golf course stream described above [Note: this stream is clearly indicated on Map 1 from 1952, prior to construction of the Parkway; curiously, however, it is not shown on Map 2 from 1984, even though our information indicates that it was present] 2) continuing from this confluence along Papermill Creek proper to a point approximately 200 m downstream from the second overlook. Maps from the colonial period indicate that the upper flow was historically a second order stream derived from three first order streams; these original sources have been completely destroyed by urbanization. For purposes of this report, "Papermill Creek" will refer to this combined area, but it is not known if the term was ever applied historically to the upper area . To help with interpretation of stream data, as described below, the pond located immediately adjacent to the Parkway in the vicinity of the Williamsburg Lodge (north of Newport Ave.) was also sampled, for chemical analysis only. Brief additional biological sampling was conducted on the outflow from the golf course ponds and on the small flow located approximately 320 m below the southern overlook.

Use of Macrobenthos to Assess Water Quality

For several decades macrobenthos analysis has been a major tool for assessing freshwater stream quality. In unpolluted streams these invertebrates are usually numerous with high taxonomic diversity. Although often difficult to identify to species, most can be identified to family relatively easily, and this level is generally sufficient for characterizing water quality reasonably well. In effect, the macrobenthos are continuous monitors of stream quality, integrating the effects of both short-duration and more-continuous environmental conditions. At both the species and family level there are wide variations in tolerance to disturbance. As a result, useful analysis and interpretation can be made on the basis of broad indexes (e.g., total taxa diversity) as well as presence/absence of specific taxa. Many “metrics” (mathematical formulas) currently exist for quantifying macrobenthos data. As a basic tool in analysis, taxa have been classified at the family level regarding pollution tolerance on a 0-10 scale, with lower values indicating low pollution tolerance and higher values indicting greater tolerance. Interpretation is greatly enhanced if such data can be combined with other information, such as chemical data, observations of the physical condition of the stream, and historical information about stream and watershed use.

Reference Areas

A fundamental need in assessing macrobenthos stream data is knowledge of natural assemblages in undisturbed conditions. Community composition may vary widely even under pristine conditions depending on specific stream structure and other variables, such as substrate type, current speed, and water chemistry. Stream conditions typically vary substantially among geographic regions; thus in Virginia the sluggish, siltier coastal plain streams differ substantially from faster-flowing gravel-substrate streams in the mountains. It is therefore important that reference areas be identified; these are sites similar to those being sampled that are thought to be as undisturbed as possible, providing a baseline against which a given set of findings can be judged. Unfortunately relatively little reference information is available for the coastal plain area of Virginia. Over the past few years, however, the Virginia Department of Environmental Quality has sampled a site on Baptist Run in York County, within the Yorktown Battlefield area. This site is thought to be reasonably satisfactory as a reference. Additionally, student research at the College of William & Mary has provided substantial information about macrobenthos composition in two small undisturbed streams within the College Woods Preserve area.

Preliminary Observations

Preliminary observations in August 1998 indicated several key stream features. The main “source” of the stream appeared to be a storm drain pipe located on the west side of the Parkway immediately south of the on/off exchange ramps between the Parkway and Newport Avenue (see Map 2). The origin of, or inputs to, this pipe were not immediately apparent. Other storm drains were present in the immediate vicinity, but had little or no flow. Water temperature was quite high at about 29 °C, and remained elevated throughout the upper area in comparison with similar well-shaded streams of the same size at that time of year (which typically do not exceed about 22 °C). Specific conductance (hereafter referred to as “conductivity”), an index of the total amount of dissolved material in the water, was very high in the upper area, at a value of about 1100-1150 umhos. Other streams in the area typically are in the 50-400 umho range. The exact relationship between conductivity and Total Dissolved Solids (TDS) varies depending on the amounts of specific solids. However, as a general approximation for many areas, the following relationship can be used: TDS = .7(umhos conductivity). This yields a value of approximately 750-800 mg/l TDS for Papermill Creek. “Fresh water” is usually defined as having less than 500 mg/l TDS. Therefore Papermill Creek appeared to be in the low-brackish range. Downstream, near the second Parkway overlook, conditions moderated a little, with somewhat lower temperature and conductivity values. In effect, however, the stream was essentially a warm, near-brackish kind of habitat, rather than the relatively cool freshwater habitat expected under natural conditions.

The stream’s banks and substrate appeared to be fairly natural in most areas, although bank extent was limited in many locations by the close proximity of the Parkway. And although banks were generally vegetated, numerous storm drains along the Parkway allowed direct access to the stream. Substrate consisted mostly of a mix of sand and silt that is typical of coastal plain streams. In some areas artificial channelization and substrate modification appeared to have occurred as a result of construction activity in the immediate vicinity. Overall, however, there appeared to be satisfactory habitat for a typical variety of macrobenthos; in addition to the sand/silt substrates, sticks and snags were present as well as decaying leaf litter. In the immediate vicinity of the culvert at the northern Parkway crossing, larger rocks and gravel were also present, adding an additional habitat type less typical of coastal plain streams.

Despite this habitat diversity, the stream was immediately noteworthy for the near absence of macrobenthos. In the upstream areas, casual collecting indicated the presence of only *Physidae*, a family of snails with a very high tolerance value. Downstream, beginning at approximately the first overlook, *Gammaridae* were also present; these are a family of crustaceans known as amphipods. Although this family as a whole is formally assigned a relatively low tolerance value, the actual species present in Papermill Creek (see below) appears to have very high tolerance abilities.

Sampling

Sample sites, used variously in both the chemical and biological sampling, were established as follows (see Map 2). Site 1 was in the stream’s uppermost area, approximately 10 m below its origin and just below the confluence of the channels from the storm drains. Site 2 was located immediately below the culvert at the stream’s first Parkway crossing. This site appeared to be the most favorable for benthos in terms of habitat structure and complexity, containing a mix of larger rocks and gravel, sticks, and abundant leaf litter, in addition to areas of sand and silt. Site 3 was located east of the first Parkway overlook. Site 4 was located 10 m below the dam associated with the beaver pond. Site 5 was located approximately 200 m below the second Parkway overlook.

Physical/chemical data were collected using standard instruments and procedures. Oxygen and temperature were measured using a YSI Model 57 meter, and conductivity with a YSI Model 33 meter with values standardized to 25 °C. Chemical analyses were conducted using a variety of Hach Company methods, including titrations as well as colorimetric procedures involving a DR/2010 spectrophotometer; results given in tables are means of two samples. Sampling dates, sites, and type of data collected, as described in Tables 1-6 and discussed below, were determined on the basis of the information judged most essential to understanding the stream's apparently unusual characteristics. Except as noted below, no significant rainfall occurred within 5 days prior to any sampling; during rain-free periods the single flowing pipe described earlier appeared to be the only significant surface source above the golf course stream.

Macrobenthos sampling was conducted on October 21, 1998 by two workers each spending a total of .5 hr at each site. Sampling at each site was conducted, and modified as necessary, in a way judged to be satisfactory and sufficient for collecting all common organisms, and with a high probability of finding rarer ones as well. Leaf litter and substrate to a depth of 10 cm were sampled using 600-micron nets and sieves. Sticks and larger rocks were inspected and any organisms removed by picking; any artificial materials (drain tile fragments, cement blocks) were similarly inspected. Bank edges and mid-stream areas were included, as well as both pool and higher-current zones. To thoroughly sample available habitats, up to approximately 15 m of stream length were searched as necessary. The amount of time spent and the diversity of habitats sampled make it very unlikely that any common taxa were missed. Based on our experience in sampling a variety of streams in the same vicinity, this effort should have been sufficient to find many rarer forms as well.

Results and Interpretation: Physical/Chemical

The first chemical analysis of Papermill Creek, in mid-August 1998, confirmed the stream's unusual characteristics (Table 1). Temperature in the upper area appeared to be elevated, given that the source appeared to emanate from underground and that most of this area is well-shaded. Streams with similar characteristics in this area, at that time of year, typically do not exceed 22 °C, whereas the temperature in Papermill Creek was 29.0 °C. Most noteworthy, however, was the apparent overall amount of dissolved material in the stream, as well as the amount of some specific components. As noted earlier, the conductivity value of 1150 umhos is well above typical values. Some of the specific constituents also exhibited anomalous values. Chloride, for example, typically occurs at levels of 10-20 mg/l, but occurred at about 130 mg/l in Papermill Creek. Calcium, on the other hand, was lower than expected: typical values are approximately 120 mg/l (expressed in units of $CaCO_3$), but Papermill Creek had a value of only around 40 mg/l in the upper area. Alkalinity (a measure of the water's resistance to acidification, or "buffering" ability) is derived primarily from the presence of carbonates and bicarbonates, and is expressed in the same units as calcium. Typically it is of about the same value as calcium (i.e., around 120 mg/l). However, alkalinity, in contrast to calcium, was distinctly elevated at a value of about 250 mg/l. Thus, in comparison to typical surface water in the general area, Papermill Creek exhibited overall increased dissolved materials, with increased chloride, increased alkalinity, and reduced calcium.

These trends were somewhat moderated downstream at Site 5, suggesting a small influence from more-typical surface water.

Two other variables are of special interest: oxygen and phosphorus. Even in the absence of disturbance, oxygen level varies significantly with temperature, declining as temperature increases. The oxygen levels observed in the Creek on August 17, which were around 5-6 mg/l, represent about 75% saturation for the given temperature. Although this level of saturation is not extremely low, the actual amount of oxygen present is probably insufficient for supporting various macrobenthos associated with undisturbed conditions.

Phosphorus, expressed here as mg/l orthophosphate, is usually the key limiting nutrient in aquatic systems, responsible for excess algal and plant growth when elevated. Although the levels reported here are well into the range associated with problems, they are not atypical for disturbed streams in this area subject to urban run-off. The creek itself (not including the beaver pond) did not exhibit any excess algal or plant growth.

Although no firm information was available on the source of the headwaters of Papermill Creek, circumstantial evidence suggested the small pond system behind the Williamsburg Lodge (see Map 2) was a likely candidate. Water from the pond is discharged directly underground, and from that point the general topography involves a downward slope toward Papermill Creek. Therefore we sampled the pond and the uppermost area of the Creek (Site 1) on September 9. This data (Table 2) provides information on the general consistency of conditions in Papermill Creek (by comparing Site 1 data in Tables 1 and 2), and on the likelihood of the pond as the main source. Conditions in the Creek were similar to those three weeks earlier, with the same anomalies regarding chloride, calcium, alkalinity, and overall dissolved materials. Conditions in the pond showed the same characteristics, and to a somewhat greater extent. Thus it appeared likely that the pond was the primary source, probably with underground input that altered the chemistry somewhat by the time it reached the start of Papermill Creek. The higher oxygen level at Site 1 in the September data reflects the supersaturated conditions occurring in the pond (13.5 mg/l), apparently as a result of the extreme growth of both algal and macrophytic organisms.

Source of the Pond Water

A major source of the pond water, and hence of Papermill Creek, is deep ground water used for heat dissipation purposes by Colonial Williamsburg. According to Mr. Tom Peck, Director of Facilities Management for Colonial Williamsburg, CW established several deep (approximately 170 m) wells in the Colonial area in the late 1950's. Water from these wells is used to remove heat from condensers involved in air conditioning. The system is flow-through rather than recirculating, with the water continuously discharged to the small pond behind the Williamsburg Lodge. This pond also receives general storm-water runoff.

Groundwater from the depth indicated above has characteristics similar to those seen in the pond and in Papermill Creek, including reduced calcium but increased chloride and alkalinity. Such water is also high in sodium (not measured by us). Mr. Peck provided data for one of the wells, confirming the above. The well values in regard to the key variables discussed here are more extreme than in either the pond or the Creek (i.e., even greater alkalinity and chloride, and less calcium). Therefore it appears that the well water is moderated to some degree both in the pond and during its underground flow to the Creek, but not sufficiently to bring it into normal freshwater condition.

Additional Data and Stream Characteristics

Data for temperature, conductivity, and oxygen on October 21, 1998 and January 29, 1999 are indicated in Tables 3 and 4. Consistent with the use of the source water for heat dissipation, temperatures at Site 1 remained elevated above those expected for that time of year, but were near normal at the lower end of the study area below the second overlook. Conductivity did not change significantly from upstream to downstream, however; this suggests that the cooling was due primarily to air contact rather than to any large input of cooler surface water. Consistent with expected temperature effects, oxygen was relatively high in the downstream water in October, and in both the upstream and downstream areas in January.

Changes Following Significant Rainfall

During approximately a 24-hr period on March 14-15, 1999 a major rainstorm occurred (actual amount of precipitation in the Williamsburg area was not determined, but was probably about 2 inches). The Creek was sampled on the morning of March 15, near the end of the storm. At Site 1, in addition to a substantially increased flow from the pond pipe, another drain was contributing a large amount of water as well. Although the exact origins of this drain are not known, it presumably contained primarily surface run-off from the storm. Samples were taken and analyzed for the storm drain water and for the Williamsburg Lodge pond, as well as for Sites 1 and 5 (Table 5).

Consistent with the expected relatively dilute nature of rainfall run-off, conductivity in the pond was reduced to 620 umhos, and at the storm drain it was 220 umhos. Shortly downstream at Site 1 it was 240 umhos. At site 5 it was only 160 umhos; this further reduction was probably due to some combination of increased dilute flow from the golf course stream and rapid, direct flow from the Parkway into the lower reaches. Other constituents changed in the various sample locations in a way consistent with a general input of surface fresh water.

Three days later (March 18, 1999) there was no evidence of flow from the storm drain. Resampling at Sites 1 and 5 indicated they had changed significantly back toward their "normal" non-storm conditions (Table 6, in relation to values in Tables 5 and 1).

Conductivity was again elevated, and levels of various constituents were closer to those reported in Table 1.

Results and Interpretation: Macrobenthos

Macrobenthic taxa and numbers collected at the five sites are listed in Table 7. Only 3-4 taxa were found at each site, and only seven total for the stream. These results may be put in perspective by comparison with the reference areas described earlier. In Baptist Run, collection at a single site (probably involving less total effort than ours in Papermill Creek) typically results in about 10-12 taxa, and a total of 5 collections would probably result in at least 20 taxa. In the College Woods streams, even higher numbers of taxa would be found with equivalent effort. It is also noteworthy that two of the taxa in the Papermill Creek sample were represented by only a single individual, and another by only three individuals. Thus Papermill Creek can be characterized as severely reduced in macrobenthic diversity.

Additional insight can be gained from the specific taxa present. In undisturbed streams many families with low tolerance values are found. Many of these belong to three major orders of insects: Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies). Most families in these groups are sensitive to disturbance and have tolerance values of 3 or less. Thus the number of "EPT" families in samples is commonly used as another general index to water quality. In Papermill Creek one EPT family was present in the form of the Trichopteran family Hydropsychidae. However, this family is known to be relatively tolerant, with an assigned value of 6. In the Williamsburg area it is commonly found in disturbed areas, and therefore its presence in Papermill Creek is not indicative of high water quality.

Chironomidae are a family of midges that includes a wide range of tolerance values at the species level. However, most species are relatively tolerant and the family is typically assigned a value in the 6-9 range. The Calopterygiidae are a family of dragonflies with an assigned value of 5. Sialidae are known as alderflies, with a value of 4. Physidae are snails, and Sphaeriidae are small clams; each has a value of 8. Gammaridae are amphipod crustaceans with a value of 4.

Although some of these more moderate values may suggest a lower level of disturbance in the stream, interpretation is complicated by the fact that individual species may differ significantly within a family regarding tolerance. Particularly noteworthy in this regard are amphipods in the Williamsburg area, specifically two species: *Gammarus fasciatus*, which is the species occurring in moderate abundance in Papermill Creek, and *Gammarus pseudolimnaeus*. Both are members of the family Gammaridae, but they appear to differ significantly in regard to tolerance, as follows.

In the Williamsburg area, *G. pseudolimnaeus* is known only from what appear to be minimally disturbed or pristine habitats; it is abundant, for example, in small undisturbed streams in the College Woods on the William & Mary campus. *G. fasciatus*, on the other hand, commonly occurs in highly disturbed areas, such as Lake Matoaka and the small streams on the developed (campus) side of Lake Matoaka. It appears likely that, historically, freshwater streams in the Williamsburg area were dominated by *G. pseudolimnaeus*, but that *G. fasciatus* has gradually moved into almost all areas as each fell victim to disturbance. Also, although *G. fasciatus* is a fully freshwater species, there is reason to believe it may have greater salinity tolerance than *G. pseudolimnaeus*; this may be another factor in its occurrence in Papermill Creek. In any case, the presence of "amphipods" in Papermill Creek cannot be used as a positive sign, given the particular species. And, overall, the extremely low taxa diversity is the key observation suggesting severe disturbance.

Further insight comes from brief sampling in early April 1999 for amphipods in the stream from the golf course ponds (Map 2) and in a small seep crossing the Parkway approximately 320 m south of the second overlook (Site 6 on Map 2). In the golf course stream conductivity was 370 umhos, a normal reading for surface water in this area that further confirms the unnatural levels in Papermill Creek. Amphipods were abundant, consisting exclusively of *G. fasciatus*. This is consistent with the general expectation that that this stream, while apparently not severely degraded, probably suffers from various disturbances. In the small seep further south, conductivity was about 330 umhos. Again, amphipods were abundant, but in the form of *G. pseudolimnaeus*. This stream, like those in the College Woods, originates and flows mostly within a protected wooded area.

Our finding of *G. pseudolimnaeus* is important in that it establishes for certain that this species was, in all likelihood, historically present in the Papermill Creek drainage. It is highly likely that at one time this species was dominant in the entire drainage; now it is reduced to a remnant population in a small, still-undisturbed area.

It is not possible at this time to sort out exactly the ways in which the various disturbances in Papermill Creek affect specific components of the benthos. Although some freshwater benthic families are known to occur well into brackish water, it is likely that the elevated salinity eliminates a significant number that are typical of undisturbed waters. Perhaps more important than the elevated salinity per se are the salinity fluctuations associated with rain. Although freshwater organisms of necessity must accommodate fluctuations in salt content, the rapid and large shifts suggested by our data, encompassing a range not normally experienced naturally, probably eliminate additional species. The warm temperature may also be important to some. For example, *G. pseudolimnaeus* is not known to occur in this area above about 23 °C; the August values we observed, near 30 °C, may account for its absence. Oxygen may also be limiting; as noted earlier, the values in the warm water during summer were relatively low in terms of absolute amount. At warmer temperatures, metabolic need for oxygen increases rapidly, and it is likely that some forms could not occur at this combination of temperature and oxygen.

The salinity, oxygen, and temperature conditions seen in our work have probably been present for a long time (approximately 40 years), and may be sufficient to account for the low diversity. However, an unknown factor is the effect of the recent fuel oil spill. It is possible that diversity was higher prior to the spill, and that organisms that can still generally tolerate conditions in the stream had not yet recolonized the area at the time of our sampling (just six months after the spill). However, there is no information on the community prior to the spill, and no exact information on the severity of the spill.

The Future

Mr. Peck has indicated that the air conditioning system using the deep groundwater will be replaced within approximately two years with a system not requiring continuous-discharge water. This will remove a major factor that is probably important in preventing a normal freshwater assemblage of benthic organisms, and may provide an excellent opportunity for observations of recolonization processes. However, it is difficult to predict whether and to what degree the stream will recover. To a significant extent the stream will continue to be impacted, at least periodically, by urban run-off, with the usual possibilities for degradation. Also, a recent study has documented that once a small stream has been disturbed, the effects in terms of organisms may remain for decades after the disturbance has been eliminated.

Recommendations

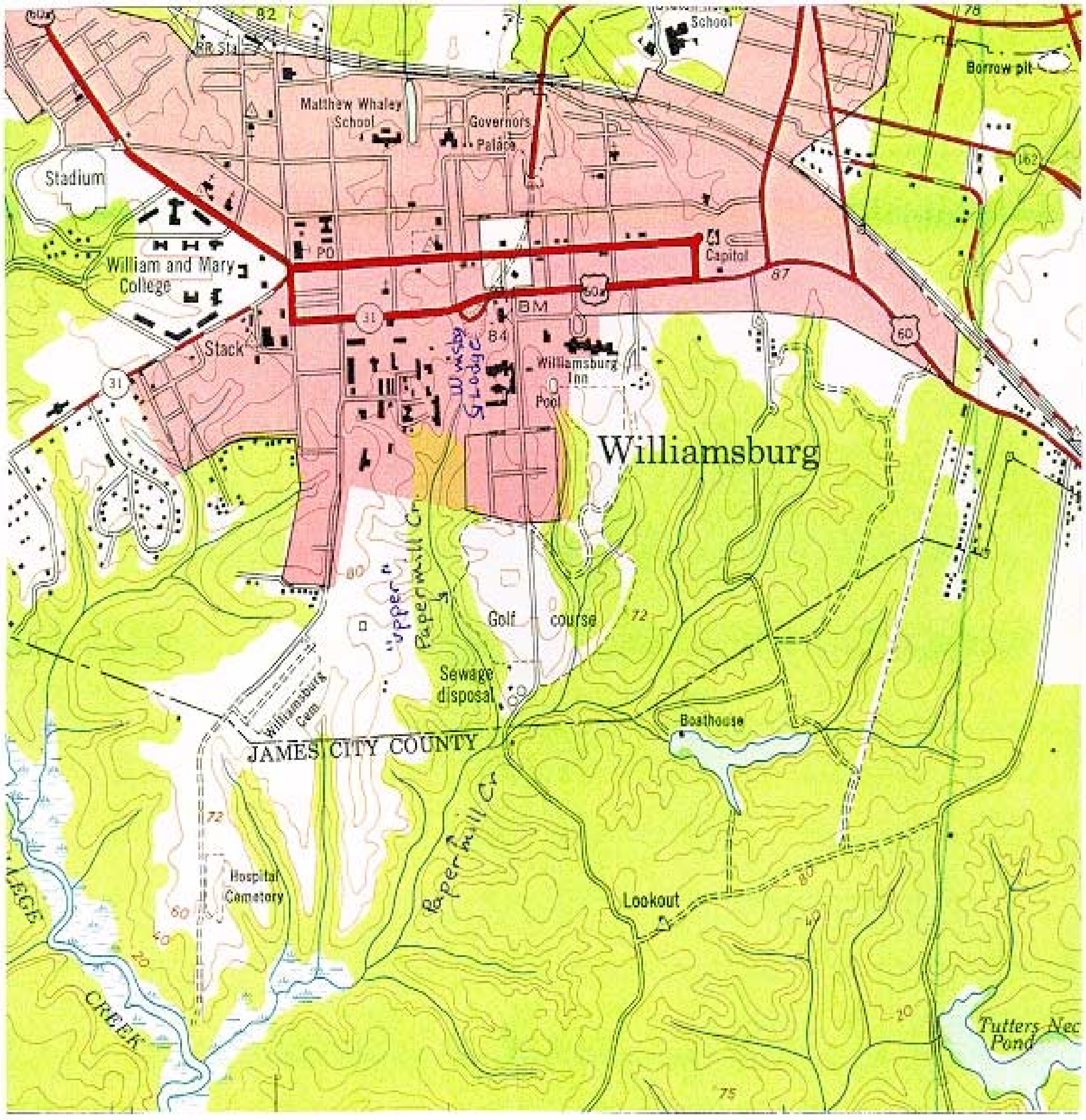
There appears to be little or nothing that CNHP can do at present to improve water quality in Papermill Creek, given that the primary impacts (urban run-off and deep ground water input) derive from areas and operations outside its control. Presumably the land controlled by CNHP in the immediate vicinity of Papermill Creek will continue to be maintained as naturally as possible regarding vegetation, to provide the general associated benefits (reduced erosion, shading to maintain cooler temperatures and to reduce problem plant or algae growth). If the groundwater input is eliminated, the stream may eventually return to better conditions, but it is likely to continue to be significantly degraded, as are almost all such habitats within urban areas, due to frequent moderate impacts (such as storm input) as well as occasional more severe events (such as the oil spill might have been). To return the stream to near-natural conditions would probably require some kind of storm-water management system involving one or more retention basins; cost and siting considerations would probably make this unfeasible.

Perhaps the most realistic perspective on Papermill Creek, in terms of environmental priorities in our current context of pervasive human impact on natural systems, is as follows. It is in reality a rather small area of (potential) freshwater habitat, now serving essentially as a short conduit carrying degraded water to a much larger and saltier system. Although any loss of natural habitat is regrettable, efforts to remediate the stream would probably require much time and expense with uncertain prospects for success. And even if successful, the benefits would be relatively small in terms of the size of habitat involved. Given limited resources, it is probably better for CNHP to focus on preservation or remediation in areas that are more valuable in terms of both size and habitat complexity. For example, the Yorktown Battlefield area contains diverse stream habitat (including flows similar to what Papermill Creek would be like under more natural conditions); water quality within this area appears to be generally good, supporting appropriate aquatic communities. If prioritizing is necessary, a focus on the Battlefield area would be far more valuable than one on Papermill Creek.

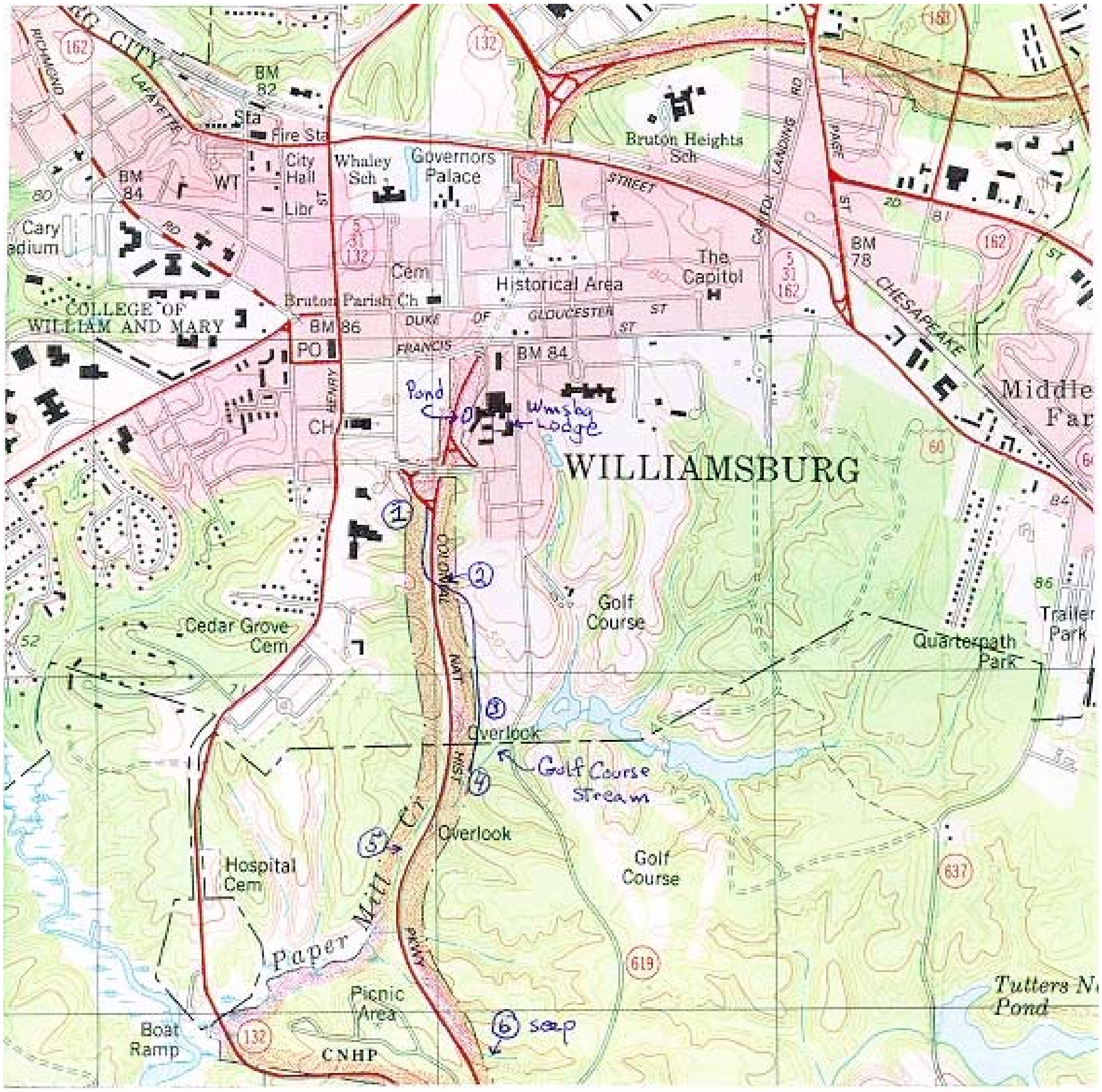
Some further small-scale organismal sampling in the Papermill Creek drainage would be useful. For general inventory purposes, collections should be made in the Beaver Pond, which was not included in the work described here. A variety of organisms typical of lentic (standing water) habitats are relatively tolerant of disturbance, and probably occur in this area. We plan to undertake such sampling this fall.

It would also be useful to resample the sites described here in Papermill Creek in the coming fall or next spring; this would be after another period of potential colonization for a variety of benthic organisms. As noted earlier, it is not known to what extent the oil spill may be responsible for eliminating particular groups. An increase in diversity in the short term would suggest that general stream conditions, in the absence of occasional severe impacts, are not quite as bad as the current data suggest.

Finally, communication with Colonial Williamsburg should be maintained to determine their exact plans for the ground-water-dependent cooling system. If this system is eliminated, baseline chemical and biological sampling should be conducted on the "new" stream water shortly thereafter. Papermill Creek might then serve as an interesting basic research area where questions about colonization rates and mechanisms for various macrobenthos could be addressed.



Map 1: Study area (USGS, Williamsburg, 1952), prior to construction of the Parkway southward from Williamsburg. The stream flowing north/south immediately west of the golf course is equivalent to the “upper” area of Papermill Creek in this study. See Map 2 for comparison.



Map 2: Study area (USGS, Williamsburg, 1984). Upper area of "Papermill Creek" is not shown on original map, but is located approximately as indicated on Map 1 and as drawn in here. Numbers refer to sampling sites (see text).

August 17, 1998

	Site 1	Site 5
Temperature (°C)	29.0	28.0
Conductivity (umhos)	1150	990
Oxygen (mg/l)	6.6	5.5
pH	8.2	8.0
Chloride (mg/l)	132	124
Alkalinity (mg/l $CaCO_3$)	250	225
Calcium (mg/l $CaCO_3$)	41	89
Sulfate (mg/l)	10	12
Silica (mg/l)	8.5	5.5
Orthophosphate (mg/l)	.16	.11
Nitrate (mg/l)	.5	.7

Table 1: Physical/chemical variables at the head of Papermill Creek (Site 1) and downstream below the second Parkway overlook (Site 5).

September 9, 1998

	Site 1	Wmsbg Lodge Pond
Temperature (°C)	27.0	28.0
Conductivity (umhos)	1050	1170
Oxygen (mg/l)	8.8	13.5
pH	8.1	8.3
Chloride (mg/l)	135	180
Alkalinity (mg/l $CaCO_3$)	246	290
Calcium (mg/l $CaCO_3$)	46	15
Sulfate (mg/l)	10	22
Silica (mg/l)	9.0	8.7
Phosphate (mg/l)	.17	.15
Nitrate (mg/l)	.6	.5

Table 2: Physical/chemical variables at the head of Papermill Creek (Site 1) and in the small pond near the Williamsburg Lodge, believed to be the primary source of the upper area of Papermill Creek.

October 21, 1998

	Site 1	Site 2	Site 3	Site 4	Site 5
Temp	27.5	22.5	19.8	18.0	17.0
Conductivity	1005	995	990	1000	1005
Oxygen	6.8	6.2	7.8	6.8	9.0

Table 3: Temperature (°C), conductivity (umhos), and oxygen (mg/l) values along Papermill Creek. From left to right data represent upstream-downstream changes.

January 29, 1999

	Site 1	Site 5
Temperature	18.8	12.5
Conductivity	900	880
Oxygen	8.6	8.8

Table 4: Temperature (°C), conductivity (umhos), and oxygen (mg/l) at the upper and lower ends of the main study area.

March 15, 1999

	Pond	Storm Drain	Site 1	Site 5
Temperature	17.0	13.0	14.5	13.0
Conductivity	620	220	240	160
Oxygen	9.5	8.1	8.4	8.0
pH	7.8	7.2	7.4	7.4
Chloride	39	5	15	12
Alkalinity	90	84	89	121
Calcium	20	97	102	114
Sulfate	29	36	32	27
Silica	9.9	4.5	5.4	8.8
Orthophosphate	.50	.18	.41	.20
Nitrate	1.2	4.5	3.0	2.6

Table 5: Values for physical/chemical variables of stream sources, and at upper (Site 1) and lower (Site 5) ends of main study area following significant rainfall. Units as in Table 1.

March 18, 1999

	Site 1	Site 5
Temperature	16.5	13.5
Conductivity	920	890
Oxygen	8.2	8.2
pH	8.0	8.1
Chloride	85	77
Alkalinity	275	268
Calcium	100	128
Sulfate	31	22
Silica	2.0	4.9
Orthophosphate	.49	.17
Nitrate	1.4	1.5

Table 6: Values for variables at upper and lower ends of main study area three days after significant rainfall. Units as in Table 1.

October 21, 1998

	Site 1	Site 2	Site 3	Site 4	Site 5
Physidae	24	3	21	9	2
Chironomidae	1	0	0	0	0
Hydropsychidae	0	7	0	35	3
Sialidae	0	0	1	0	0
Calopterygidae	1	7	6	2	1
Sphaeriidae	0	0	0	3	0
Gammaridae (*G. fasciatus)*	0	13	80+	80+	14

Table 7: Macrobenthos at five sites in Papermill Creek. See text for discussion.